Long Life/Low Maintenance Thermal Protection System

The development of a long-life/low-maintenance thermal protection system is required to decrease the operational costs of reusable vehicles. Tasks to investigate metallic concepts, toughened rigid ceramic insulation, advanced flexible blanket insulation, carbon/silicon-carbide hot structures, and direct-bond reusable surface insulation are included in this area.

High Priority Vehicle-Unique Technology/Advanced Development

For the single-stage-to-orbit all-rocket concept, the key technology requirement is for the development of a long life, low maintenance, tripropellant engine generally based on the Russian RD–704 design. An alternate approach would be the development of appropriate technologies for an advanced lox/LH_2 engine derived from the Space Shuttle main engine.

Costs

This section includes Option 3 cost estimates over the life of the program. All transportation costs to launch NASA and Department of Defense payloads from 1994 to 2030 are included. The life-cycle costs include: the cost of operating current systems (Space Transportation System, Titan IV, Atlas, Delta) from 1994 until replacement; technology, design, development, test, and evaluation; facilities; vehicle fleet production (including production of vehicles for anticipated reliability losses); and recurring operations. In addition to the vehicle costs, the design, development, test, and evaluation, and production costs for a crew rotation module and an upper stage are included.

Design, development, test, evaluation, and production estimates are business-as-usual estimates and take no credit for potential cost savings that can be achieved by using new ways of doing business or more efficient management or procurement approaches (e.g., "Skunk Works"). A savings of 30–40 percent over these numbers could be expected if such new ways were adopted. Operations cost estimates do require a significant departure from the current Space Transportation System operations culture and reflect the ground rules and philosophy detailed earlier.

Table 7 shows the total cost from 1994 to 2030 of each cost element for the two options of the single-stage-to-orbit all-rocket vehicle using the RD–704 engine. Note that the 45-foot payload bay vehicle has significantly lower expendable launch vehicle costs since it was assumed to replace the Titan IV as well as all other current vehicles.

Figure 34 shows the cost profile from 1994 to 2030 for the architecture featuring the single-stage-to-orbit all-rocket vehicle using the RD–704 engines with a 45-foot payload bay.

Option 3 Team Findings

Comparison Against Criteria

The single-stage-to-orbit all-rocket vehicle meets the fundamental requirement established at the outset of the study to satisfy the national launch needs. The focus of the study was in defining a 25k-pound class of launcher since approximately 90 percent of all future payloads fall into this category. The advanced technology vehicle will replace all Delta- and Atlas-class missions and meet Space Station logistics resupply and return requirements (cargo and crewed). The vehicle is capable of performing on-orbit payload servicing missions when required. The tripropellant aspect also allows for an option to carry a 45-foot long payload bay to accommodate Titan IV-class payloads.

The single-stage-to-orbit all-rocket vehicle also has the potential for increasing crew safety and vehicle reliability. The vehicle is capable of performing a return-to-launch-site maneuver with one engine failure on the launch pad. Abort with multi-engine failures is possible during the ascent phase. In the crewed configuration, the crew pressure vessel is designed to survive a catastrophic failure, with ejection seats for escape. Avionics fault tolerance is fail op/fail safe. Engine shutdown is possible due to all liquid propulsion. Reliability is also enhanced through the use of a single airframe, which inherently reduces the number of vehicle systems.

Table 7.—*Single-stage-to-orbit all rocket vehicle costs*

Total Costs ($B) FY94–FY2030*

SSTO(R) (RD–704)		
	30-ft Payload Bay	45-ft Payload Bay
Technology Development	**0.9**	**0.9**
DDT&E	**16.7**	**17.1**
• Vehicle	13.9	14.3
• Crew Rotation Module	2.2	2.2
• Upper Stage	0.6	0.6
Facilities	**0.6**	**0.6**
Production	**18.1**	**18.7**
• Vehicle	12.6	13.2
• Crew Rotation Module	0.8	0.8
• Engine	4.7	4.7
Operations	**161.7**	**131.9**
• Vehicle	23.9	23.9
• STS	49.1	49.1
• ELV	85.8	56.0
• Upper Stage	2.9	2.9
Total	**198.0**	**169.2**

* Dollar amounts given in FY94 values.

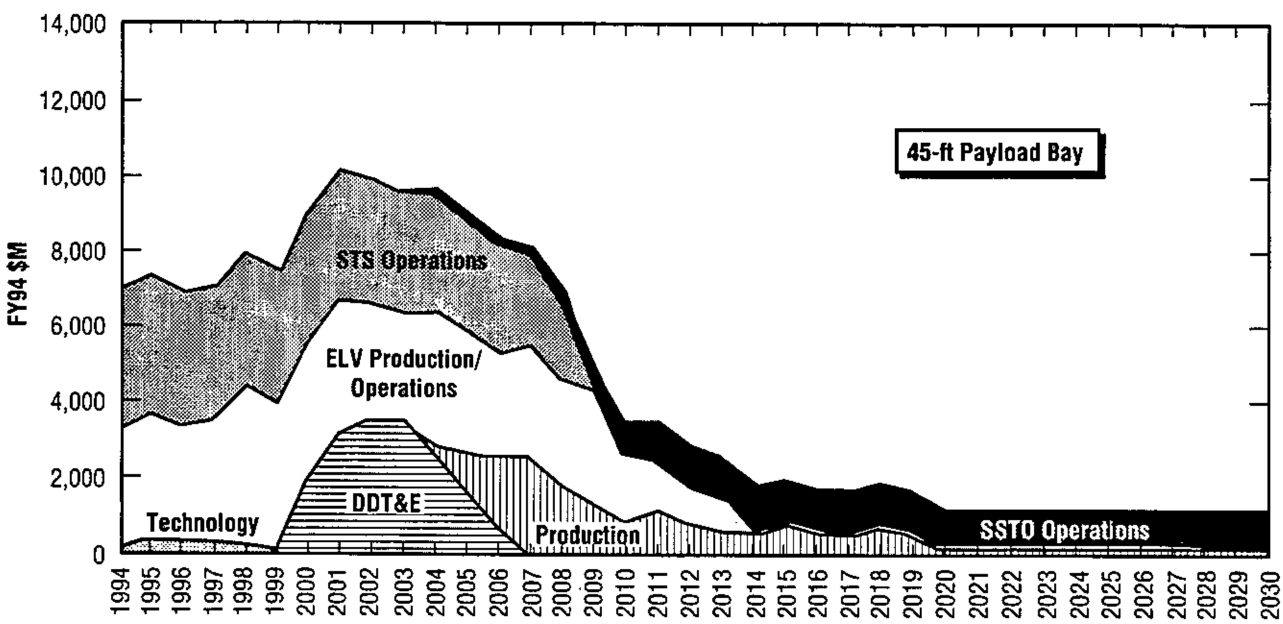

Figure 34.—**Access to Space Option 3 single-stage-to-orbit all rocket total cost spread.**

The focus of the Option 3 effort was on reducing annual operations costs. The single-stage-to-orbit all rocket annual operating costs are estimated to be approximately one-third that of the Space Shuttle. This is possible through the use of a single, fully reusable airframe coupled with changes in the space launch operations culture. Development costs of approximately $18B were estimated using a NASA business-as-usual approach and appear reasonable for this type of system. A 30–40 percent reduction could be expected with new ways of doing business. Even without flying the Titan IV payload missions, payback on the initial investment will occur approximately 9 years from initial operating capability. Risk is mitigated though the use of evolutionary technologies based on proven systems and a technology maturation program prior to initiation of full scale development, coupled with a prototype test vehicle to reduce both technical and programmatic risk. If the technologies do not mature prior to full-scale development, the option exists for terminating future development and applying the technologies to the existing expendable and Shuttle launch vehicle fleets.

A high flight rate coupled with full reusability will yield cost-effective and competitive space access for commercial payloads. The Option 3 recommended program is focused on technology development and application that will result in a significant technology data base for use by the private sector. Potential dual-use technologies include applications to existing and future launch systems and high-strength/lightweight composite structures.

Summary

The Option 3 team has defined a strategy to meet reduced cost future space transportation needs, with a primary focus on improving reliability, crew safety, and operability. An approach has been defined that will offer significant reductions in annual operations costs. The advanced technology approach, Option 3, meets these needs by defining a transportation architecture that contains an all rocket single-stage-to-orbit launch vehicle to accommodate both Space Station resupply and 25,000 to 41,000 pound cargo delivery and satellite deployment missions (NASA, DOD, and commercial) in CY2008, as well as an interim expendable launch vehicle program that upgrades the existing Delta, Atlas, and Titan fleet in the CY2000 to 2008 time frame. The final architecture of Option 3 is shown in figure 35.

Based on preliminary evaluations, single-stage-to-orbit vehicles appear to be feasible because of reduced sensitivity to engine performance and weight growth resulting from use of near term advanced technologies (e.g., tripropellant main propulsion, Al-Li and graphite composite cryogenic tanks, graphite-composite primary structure, etc.). An incremental approach has been laid out to reduce both technical and programmatic risk. This includes maturing the required technologies to a technology readiness level of 6 prior to full-scale development (i.e., ground tests and experimental vehicles) and conducting a prototype flight test program that will define the operational envelope of the vehicle and thus certify the design for production and operations.

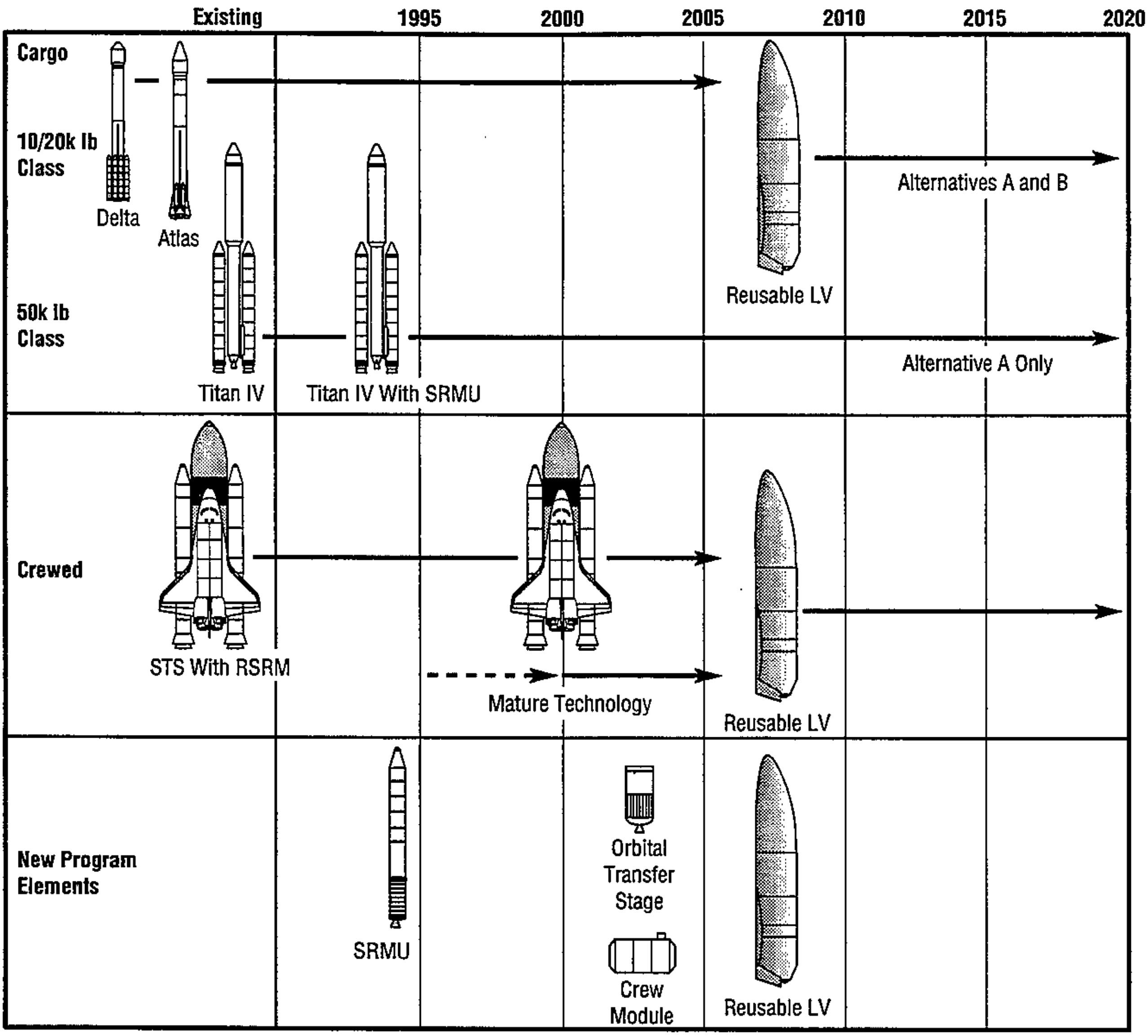

FIGURE 35.—**Advanced technology architecture.**

The goal to lower the cost of routine access to space has been demonstrated in this option with a fully reusable launch vehicle that captures Delta, Atlas, Titan, and Shuttle missions at approximately 20 percent of the current combined annual operating costs of these systems.

Affordable, routine access to space will only be achieved when today's space flight infrastructure is decreased substantially. This is particularly true in the area of operations where vehicle processing, mission planning, and flight execution must be significantly streamlined. Improvements can and should be made in the existing Delta, Atlas, Titan, and Shuttle systems with infusion of advanced technologies and streamlined management techniques. However, the basic high-cost infrastructure will remain due to the design characteristics of the vehicles—multiple stages, solid stacking, ocean recovery and reconditioning, performance limitations, and so forth. The single-stage-to-orbit all-rocket vehicle is capable of delivering these necessary infrastructure reductions through the use of technology enhancements that offer increased margins simultaneously with major increases in operability. Additionally, a large portion of the reduction can be attributed to the elimination of major systems such as the external tank, solid rocket boosters, multiple stages, and so forth.

The bottom line is this: operability must not be simply a goal; it must be THE design driver.

Option Team Down-Selects

The most beneficial architectures as recommended by the Option teams are shown in the shaded areas in figure 36. These architectures were presented to the study steering group. They were then subjected to comparative analysis from which a preferred architecture was to be selected.

Option 1	Option 2	Option 3
Shuttle-Based	Conventional Technology	New Technology
• **Retrofit: Evolutionary improvements. Keep the current ELV fleet.** • New Build: Above changes plus major internal mods; new orbiter. Keep the current ELV fleet. • New Mold Line: Above changes plus major external mods; new orbiters and boosters. Keep the current ELV fleet.	• 84 configurations with differing crew carriers, cargo vehicles, stage configurations, engine types, and number of new vehicles. Reduced to four primary candidate architectures: – (2A): New large vehicle • Keep Atlas, Delta ELV's • HL–42 plus ATV – (2B): New lg. and sm. vehicle • Keep Delta ELV • CLV-P for crew plus cargo – (2C): New lg. and sm. vehicle • Keep Delta ELV • HL–42 plus ATV • Hybrids; STME engines **– (2D): New lg. and sm. vehicle** **• Keep Delta ELV** **• HL–42 plus ATV** **• RD180/J2S engines**	• **3A: Single-stage-to-orbit all rocket – With Titans** • **3B: Single-stage-to-orbit all rocket – No ELV's** • Single-stage-to-orbit air-breather/rocket – No ELV's • Two-stage-to-orbit air-breather/rocket – No ELV's

FIGURE 36.—Architectural alternatives proposed by the teams.

The Option 1 team down-selected to the Retrofit Alternative. This is the alternative that incorporated only internal changes to the Space Shuttle orbiter, retrofitted them into the fleet as the orbiters came in for major maintenance, and replaced orbiters only for attrition. The rationale for the down-select was that this alternative had the lowest design, development, test, and evaluation cost, while enabling about the same level of annual operations cost savings as the other alternatives.

The Option 2 team down-selected to the 2D architecture. This is an architecture that built a new expendable 20k-pound payload launch vehicle to replace the Atlas, a new 85k-pound lift expendable vehicle to replace the Titan and the Shuttle, separate new cargo and crew carriers, and the single-engine Centaur upper stage. It kept the Delta as a cost-effective launcher for smaller payloads. The principal reasons for the down-select were that this alternative did not require new engine development (the RD180 was claimed to be a low-risk modification of the currently operational RD170), had low life-cycle costs, and had the lowest operations costs for the Atlas-class missions, which have a high level of commercial interest. It accepted the limitations inherent in reduced down-mass capability from the Space Station.

The Option 3 team down-selected to an all-rocket, fully reusable single-stage-to-orbit vehicle. The recommended configuration for this vehicle incorporated a tripropellant propulsion system, graphite-composite structure, aluminum-lithium propellant tanks, and an advanced thermal protection system and subsystems. Added margin could be attained by using graphite-composite fuel tanks rather than those made with aluminum-lithium fuel tanks. Rocket vehicles were selected over air-breathing vehicles on the basis that they had lower design, development, test, and evaluation costs; lower technology phase costs; and required less demanding technology that would translate into a more quickly developed and less risky program.

Two versions of the single-stage-to-orbit rocket were recommended. The first (Option 3A) had a transverse payload bay 15 feet in diameter and 30-feet long, which could not accommodate the largest of the Titan-class missions. This architecture thus required continuation of the Titan expendable launch vehicles in parallel with the new vehicle operations. The second version of the single-stage-to-orbit rocket vehicle (Option 3B) had a 45-feet long longitudinal payload bay that could accommodate all Titan payloads if some were somewhat downsized (a plan which is under serious consideration within the Department of Defense), and thus would not require continuation of expendable launch vehicles as part of the architecture. This version was included because of the high costs of operating the Titan expendable launch vehicle.

New Operations Concept

All the option teams recognized that if large savings in annual costs were to be realized, new management, contracting, design, development, and, particularly, operations concepts had to be devised. The fundamental change required was that all phases had to be driven by efficient operations rather than by attainment of maximum performance levels. This, in turn, required maximizing automation and minimizing the number of people in the "standing army" on the ground, as well as requiring redundancy, engine-out capability, and robust margins in all subsystems. In addition, both of the Options 2 and 3 teams recommended avoiding development of new technology in parallel with vehicle development in order to minimize program risks and cost growth.

The Options 2 and 3 teams recommended a streamlined management and contracting approach patterned after the Lockheed "Skunk Works," which features smaller, but dedicated and collocated government oversight, a more efficient contractor internal organization, rapid prototyping, and team continuity from design to flight.

The recommendations also included a number of specific operations-oriented items, some of which are applicable to reusable vehicles and others that apply to both expendable and reusable vehicle operations. They included using well-matured technologies, demonstrated through a number of flights of an experimental vehicle; demonstration and validation of vehicle design via flights of a full-scale prototype, with gradual stretching of the flight envelope; certification of the vehicle design and type-certification of the fleet; avoiding continual engineering changes and long-term development engineering overhead by freezing the design for long periods between block changes; avoiding most detailed inspection and maintenance after each flight unless the need is clearly indicated by an onboard health monitoring and reporting system, or if the immediately previous flight exceeded the flight envelope limits charted in the prototype program; operating the single-stage-to-orbit fleet using a depot maintenance philosophy in which maintenance is only done by exception or every 1 to 2 years; use of small, dedicated ground crews led by a crew chief empowered to make all decisions in operations and maintenance; a reduced ratio of nontouch to touch labor compared to that utilized in today's operations; and much use of automation on the ground, as well as in the vehicle. These amount to a complete change in the way vehicles are developed and operated compared to current practice, and are patterned after several high-performance aircraft programs.

In the aggregate, the above recommendations amount to a "new way of doing business," which was recognized as being essential if low operating costs were to be realized. Its attainment would be a major shift from today's practices in launch vehicle operations.

Comparative Analysis

The down-selected architectures were compared so that a decision could be made on the most attractive option. The major factors considered in the evaluation were design, development, test, and evaluation costs; operations costs; life-cycle costs; and the safety and reliability of the concepts. These and other factors considered followed the major evaluation criteria identified in the Purpose section.

Costs Assessment

The costs presented in this report were developed from a common set of ground rules developed by the Comptroller's Office and are predicated on the technical complexity, operability, and flight-related assumptions of each of the option teams. The costs of the recommended architectures were analyzed, with design, development, test, and evaluation and total program costs treated separately. All cost figures are shown in constant FY94 dollars and in a business-as-usual mode, that is, without incorporation of the operations or management changes discussed in the New Operations Concepts section. This is because the NASA cost models were designed around the historical data base, and NASA does not have a mature basis for estimating costs incurred in a different culture.

The NASA Comptroller assembled a cost team to attempt to estimate the savings that might accrue if new ways of doing business were adopted, and this team concluded that a 30 to 40 percent reduction of the costs shown might be expected operating in such a mode. However, the cost team felt that since each of the options benefited differently from changes in culture, the comparison of the different options would be best served by using the business-as-usual method and then applying estimated reduction factors.

The design, development, test, and evaluation costs of the three options are shown in figure 37. These curves include a technology phase for Option 3. The curves are annotated with a callout indicating the total technology, design, development, test, and evaluation costs, which are $2.4B for Option 1; $11.1B for Option 2; and $17.6 and $18B for Options 3A and 3B, respectively. These curves do not include facilities, production, or operations. If the new ways of doing business were adopted, these costs could be as much as 30 to 40 percent lower, or $1.5 to $1.7B for Option 1; $6.7 to $7.7B for Option 2; and $10.6 to $12.6B for Option 3.

The profiles of these technology, design, development, test, and evaluation expenditures are very different. Options 1 and 2 require large budgets essentially immediately, while Option 3 has a 4 to 5 year technology phase funded at relatively modest levels before the large budget requirements start. This technology phase requires $900M over 5 years and has an annual peak of about $240M. The profiles of Options 3A and 3B are essentially the same.

The life cycle cost profiles of the three options are shown through the year 2030 in figure 38. These are total costs for the entire period to deliver the mission model of the Approach, Ground Rules, and Organization section, and include the technology, design, development, test, and evaluation costs of figure 37. A fourth curve is included in figure 38, labeled "current systems," which represents the cost to the U.S. Government if no changes are made and the current systems are operated for the entire period. In 1995, this current systems cost will be comprised of $3.8B for the Space Shuttle, $2.4B for the Department of Defense expendable launch vehicles and infrastructure, and $0.5B for the NASA expendable launch vehicles, totaling $6.7B.

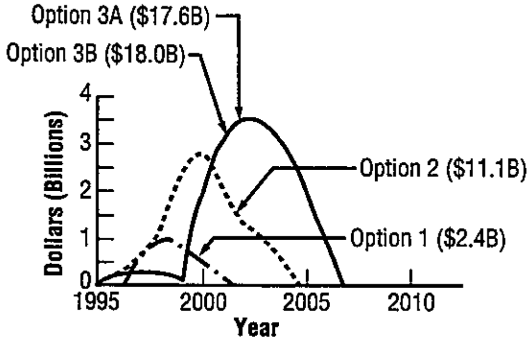

FIGURE 37.— Design, development, test, and evaluation costs of the options.

(This information applies to both figures.)

- Commercial flight costs excluded
- Technology phase included
- Constant FY94 dollars
- No credit for "new ways of doing business"
- Alternatives costed:

Option 1	– Retrofit Alternative STS plus Pegasus, Delta, Atlas, and Titan – Current upper stages
Option 2D	– Large and small new vehicles plus Pegasus and Delta – Single engine Centaur upper stage
Option 3A	– SSTO tripropellant rocket (30-ft bay) – Titan IV; plus new upper stage
Option 3B	– SSTO tripropellant rocket (45-ft bay) – New upper stage

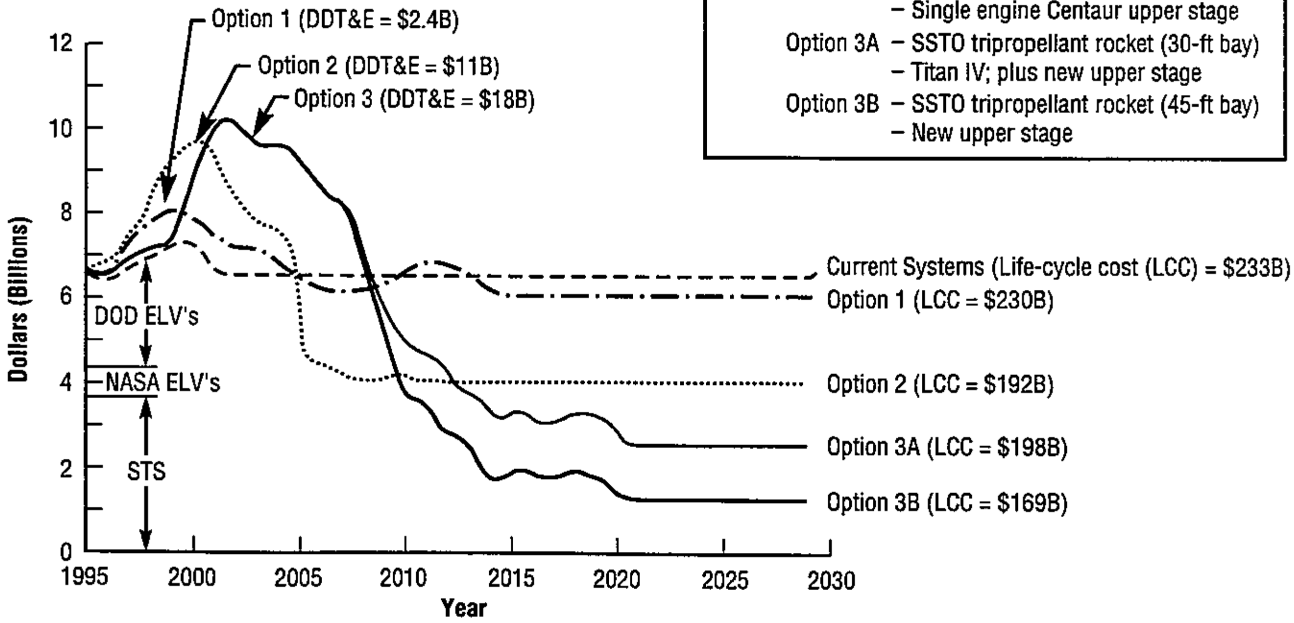

FIGURE 38.—Total U.S. Government launch costs.

This reference varies somewhat with the expendable launch vehicle annual buys, infrastructure investments, and programmed Shuttle improvements. It was assumed as a point of reference that the expenditures remain essentially fixed after 2000, and that no additional orbiters will be acquired through 2030, even though a replacement orbiter is likely to be needed sometime during that interval. The life-cycle cost of this activity, if nothing is done differently than today, is $233B through 2030.

The cost plot of the architecture of Option 1 shows the increase for the $2.4B investment, followed by the $6.5B to retrofit the fleet, and then by a programmed buy of a replacement orbiter in 2010. The annual realized savings in operations costs is only about $0.25B per year. Its life-cycle costs are $230B. The investment in design, development, test, and evaluation is recovered after 10 years of steady-state operations. The total investment including design, development, test, and evaluation, and the replacement orbiter is recovered in slightly more than 20 years of operation.

The cost plot of the architecture of Option 2 shows the investment of $11.1B in design, development, test, and evaluation costs upon the immediate start of new vehicle development, followed by a rapid reduction in the operations costs starting in 2005 when the new vehicles are introduced and the Shuttle and most expendable launch vehicles are phased out. These vehicles are all phased out over 2 years. The operating costs are reduced to $4B annually beginning in 2006. The life-cycle costs of Option 2 were $192B. The recovery time for the investment in design, development, test, and evaluation is about 4 years of steady-state operation. The recovery of the total design, development, test, and evaluation plus production investment is about 5 years of steady-state operation.

The plot of the architecture of Option 3A shows the investment of $17.6B for technology, design, development, test, and evaluation through 2008, with the start of the development program delayed by about 5 years due to the technology maturation and demonstration phase. This option features the vehicle with the shorter payload bay, which requires continuation of the Titan expendable launch vehicles in parallel.

The Option 3A architecture results in a steady-state operations cost of $2.6B per year. That level is not achieved until after 2020 due to a deliberately slow production phase for the reusable vehicles and upper stages and their spares, which are all purchased continuously and then the production line is shut down. These purchases are stretched over 10 years or more to minimize peak funding needs. The technology, design, development, test, and evaluation investment would be recovered in 4 ½ years of steady-state operations, while recovery of the total investment, including production of the vehicles, requires 9 years. The life-cycle cost of Option 3A is $198B.

Option 3B has the longer payload bay and could carry all DOD payloads with some downsizing, which the DOD may accomplish at the program's block change time in the first part of the 2000 to 2010 time period. The cost profile for this option follows that of Option 3A during development, but decreases to an annual operations cost of $1.4B since no Titans need to be retained. The life-cycle cost for this option is $169B. The technology, design, development, test, and evaluation investment would be recovered in only 3 ½ years of steady-state operation, while recovery of the total investment would take only 7 years.

The clear message from figure 38 is that new vehicles are required if substantial savings are desired, and that attaining the greatest savings requires the largest investment.

The most significant aspects of the costs of the three options, and some associated metrics, are shown in figure 39. This figure displays the costs for the technology phase, the design, development, test, and evaluation (including the technology phase), the production of one-time or reusable hardware, the annual operations costs in the out-years, and the life-cycle costs.